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AN EXPERIMENTAL ANALYSIS OF NEW ULTRA-VIOLET EMITTING FIBER OPTIC FACEPLATE CATHODE RAY TUBES

Joseph Pucilowski, Jr., et al

Army Electronics Command
Fort Monmouth, New Jersey

November 1972

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13. ABSTRACT

An experimental analysis of new ultraviolet (UV) emitting, fiber-optic faceplate cathode-ray tubes (CRT) ~~has been~~ performed. Detailed studies were carried out for a tube with emission centered near 380 nanometers (nm). Initial data taken on a tube whose emission was centered near 320 nm showed that its radiant output was below expectations, probably due to problems encountered during faceplate manufacture. Consequently, it was not possible to perform a comprehensive analysis on this tube. This study represented the first operational analysis of these CRT, and writing rates on various dry-process, UV sensitive recording media were measured for the 380 nm tube. A comparison has been made with a state-of-the-art 380 nm CRT. Theoretical calculations indicated that the new 380 nm CRT should have at least nine times the energy output of available CRT. Agreement with theoretical calculations was excellent. Results are summarized and performance is discussed.

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AN EXPERIMENTAL ANALYSIS OF NEW ULTRAVIOLET EMITTING FIBER OPTIC FACEPLATE CATHODE RAY TUBES

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AN EXPERIMENTAL ANALYSIS OF NEW ULTRAVIOLET EMITTING FIBER OPTIC FACEPLATE CATHODE RAY TUBES

INTRODUCTION

This report is concerned with the analysis of two new ultraviolet (UV) emitting, fiber optic faceplate cathode ray tubes (CRT) developed under U S Army Electronics Command contracts.* These tubes were developed for the purpose of recording upon dry-process recording media such as Kalvar, photochromics, and Du Pont materials. All of these media exhibit slow recording speeds when compared to wet process silver-halide films, and thus require relatively large amounts of energy from the radiating source to produce useful optical densities when the image is processed. Fiber optic tubes were developed in order to employ contact printing techniques, thus eliminating the need for transfer lenses with their inherently high light losses (particularly in the UV portion of the spectrum) and their high volume requirements.

The two tubes developed were designed to emit radiation centered about 320 nm and 380 nm, respectively, in order to provide a spectral match for any of the available UV sensitive recording media. The CRT are seen in Figure 1. A new phosphor was synthesized as a replacement for P-16, the commonly used UV phosphor whose spectral output peaks at about 380 nm. P-16 exhibits a very short lifetime under high energy bombardment, i.e., 0.01 C/cm^2 while the new phosphor, $ZnSiO_4:TiO_2$, has a very long lifetime, i.e., 100 C/cm^2. The latter phosphor coupled with the new fiber optic faceplate with numerical aperture of 0.88 and transmission at 380 nm of 70 percent (including losses due to Fresnel reflections) represents about a nine fold improvement in energy output when compared to P-16 coupled with existing fiber optic faceplates. The radiant output and transmission curves for the new phosphor and faceplate, respectively, are seen in Figure 2. The new 320 nm phosphor and faceplate can not be compared to any existing units since there are no fiber optic faceplate CRT which emit in this region of the spectrum. Totally new glass and phosphors had to be developed for the 320 nm CRT. The appropriate spectral curves are seen in Figure 3. Detailed theoretical evaluations of the performance of these tubes have been published as have the details of CRT construction.[1-4] However, this is the first available experimental data available on these CRT.

*Phosphor development was performed by Westinghouse Aerospace Division, Baltimore, Maryland, under USAECOM Contract DAAB07-68-C-0392.

*Tube fabrication was performed by Westinghouse Electron Tube Division, Elmira, New York, under USAECOM Contract DAAB07-68-C-0392.

*Faceplate glass for transmission at 320 nm was developed by Illinois Institute of Technology Research Institute (IITRI), Chicago, Illinois, under Contract DAAB07-67-C-0542. This faceplate was fabricated by Mosaic Division of Bendix under subcontract to IITRI.

*Faceplate glass for transmission at 380 nm was developed at Rutgers University, Ceramics Department, under subcontract to Chicago Aerial Industries under USAECOM Contract DA 28-043 AMC-02057 (E). This faceplate was fabricated by the American Optical Company.

A Litton fiber optic faceplate CRT type 4207 with P-16 phosphor was made available by Litton for comparison purposes. This particular CRT utilized an electrophoretically deposited phosphor which usually results in a somewhat less efficient screen than that which results from a settled phosphor. The faceplate contained an extramural absorber (EMA) which might have a slight effect on writing speed. Litton has performed extensive work toward improving P-16 phosphor and deposition techniques and has achieved very high initial efficiency for their screens, i.e., about 4%. Thus, this tube should represent a high state-of-the-art device. Minimum spot size is listed as 0.0015 inch and maximum anode voltage and beam currents are 30 kV, and 40 μA, respectively.

DISCUSSION

1. System Description. For this type of analysis, it is necessary to determine the energy density of the beam as accurately as possible. To accomplish this, the CRT was operated in such a manner that any single line or group of lines in a given raster could be displayed on the tube face. By recording the raster size or sweep length, sweep speeds, accelerating voltage, beam current, and spot size, the energy density of the beam could be determined. A block diagram of the electronics is seen in Figure 4. A line synchronized sawtooth generator provides the vertical input for the deflection amplifier and synchronizes the horizontal sawtooth generator and a video pulse generator. The output of the pulse generator is fed into a line synchronized gated amplifier. By controlling this pulse delay and width, any line or number of lines in the raster may be selected for display. Also, the electronics of the gated amplifier allows for selection of the number of frames over which the line or lines will be displayed; that is, the information could be gated on during only one frame or for a number of frames. Such close control is necessary for measurements of exposure of very sensitive films. The output of the gated amplifier appears at the CRT cathode after passing through a high voltage coupling amplifier. This latter unit is necessary since the tubes are operated in a grounded anode, or depressed cathode mode. Electromagnetic deflection and electrostatic focus are used for the new CRT as indicated in Figure 4. The Litton tube used for comparison purposes employed electromagnetic focus. Necessary voltage supplies are shown as is a current meter panel for monitoring dc anode current. An oscilloscope is used for measurement of current during pulsed operation. The actual experimental set-up is seen in Figure 5. Figure 6 is a closeup of the precision CRT mounting assembly. A simple spring loaded pressure plate (Figure 7) was designed to press the film being exposed directly against the fiber optic faceplate. A commercially available microdensitometer is used to measure the optical density (O.D.) of images formed on processed films.

2. Experimental Results. Samples of 3M dry silver, Du Pont Dylux, NCR Photochromic, and Kalvar films were obtained. All were transparent films, not papers. The 380 nm CRT was placed in the experimental mount and used to expose the 3M Type 784 Dry-Silver Photographic Film. The spectral sensitivity of that film is seen in Figure 8. Note that the scale is logarithmic and extrapolation of the curve further into the UV portion of the spectrum indicates that the film has a maximum sensitivity below 330 nm. This is the most sensitive of the dry process films mentioned. Heat processing is required and a hot air gun was used for this purpose. A barrel was added to the gun with a thermometer inserted in the air flow (Figure 9).

A typical process time for the 3M film is 25 seconds at 240°F or 10 seconds at 260°F. Shorter exposures and longer process times increase the gamma of the film and vice versa. Higher quality images result when lower temperatures and longer processing times are employed. For these experiments, a 50 second process time was used in order to achieve a large gamma. Air temperature, as it left the barrel, was about 250°F and the film was held about one inch below the end of the barrel for the required time to achieve satisfactory results. Such a film would be useful, of course, in systems where the volume and maintenance requirements of wet process films were unacceptable and real-time readout necessitating processing times less than 10 seconds was not a requirement. Some of the other films such as the Du Pont Dylux films allow instant readout, but are far less sensitive. Also shown in Figure 9 is the apparatus used for processing films requiring very short processing times. These films, such as Kalvar, are placed on the holder shown and swept through the hot air at a constant rate by a dc motor.

It has been shown[4] that for these tubes, the energy output in joules is

$$E = \frac{\eta F \gamma P \tau}{A} \delta \qquad (1)$$

where η = phosphor conversion efficiency

F = energy transfer efficiency from the phosphor to the outside of the faceplate

γ = phosphor utilization factor, taken to be 0.5[5]

P = beam power, in watts

τ = time beam is over area A, in seconds

δ = spectral transfer efficiency into the film

A = spot size in cm^2

Further, $F = \epsilon \, \theta_f$ where θ_f represents the collection properties of the faceplate as determined by its numerical aperature, and ϵ represents the spectral overlap between the phosphor and faceplate. Values of θ_f have been tabulated by Kapany[6] and, from the definition of ϵ, it follows that

$$\epsilon = \frac{\int_0^\infty p(\lambda) f(\lambda) d\lambda}{\int_0^\infty p(\lambda) d\lambda} \qquad (2)$$

where $p(\lambda)$ is the emission spectrum of the phosphor and $f(\lambda)$ is the transmission function of the faceplate including Fresnel losses.

The expression for δ is

$$\delta = \frac{\int_0^\infty p(\lambda)\ f(\lambda)\ S(\lambda) d\lambda}{\int_0^\infty p(\lambda)\ f(\lambda)\ d\lambda} \qquad (3)$$

where $S(\lambda)$ is the normalized spectral sensitivity of the film.

When the appropriate graphical integrations are performed and parameters measured for 3M film in conjunction with the 380 nm tube, the following values are determined:

$$\eta = 0.03$$

$$\varepsilon = 0.74$$

$$\beta_f = 0.69$$

$$\nu = 0.5$$

$$P = (20\,kV)\ (20 \times 10^{-6}\ A) = 0.4 \text{ watt}$$

$$\delta = 0.13$$

$$A = 191 \times 10^{-6}\ cm^2$$

This results in an energy $E = 208\ \tau\ W/cm^2$. From the film sensitivity curve and the phosphor spectral output curve, one can determine that 10^3 $ergs/cm^2$ are needed to achieve an O.D. of 0.6 on the processed film. Thus, τ is required to be $0.515 \mu s$. From the above figures, it is seen that this data are for 20 kV operation at 20 µA beam current and a spot size of nearly 0.006 inch. Spot size on the 320 nm tubes delivered at a later date with improved electron guns was 0.002 inch. The larger 0.006 inch spot size of these 380 nm tubes is a product of the electron optics and not of a phosphor or faceplate limitation. With improved electron guns, this phosphor faceplate combination could be employed in CRT at much higher anode voltages, much larger beam currents, and much smaller spot sizes with no degradation of the phosphor. This would result in a CRT capable of much faster writing speeds than these experimental models. Theoretical calculations thus indicate that given the operating parameters of this CRT as discussed above and given the film, phosphor, faceplate characteristics shown in the figures, an O.D. of 0.6 can be achieved at a dwell time of $0.515\ \mu s$ on the 0.0059 inch spot or, expressed differently, an effective writing speed of about 15,000 inches per second can be obtained.

When the 3M film was actually exposed, an O.D. of 0.9 was achieved at an effective writing rate of 20,000 inches per second. The tube performed better than the theoretical calculations indicated it would. Since it is only necessary to achieve an optical density of 0.3 to permit ready readability, it can be seen that even at this relatively low beam power density writing speeds of about 50,000 inches per second or greater would yield a readable copy. At about 35 kV and 30 to 50 μ A beam current into a 0.002 inch spot, use of this phosphor faceplate combination should result in a CRT capable of exposing the dry silver film at rates well in excess of 100,000 in/s. It should be noted that this 3M film is sensitive to visible radiation (Figure 8), and that the speeds indicated equal and would surpass quoted speeds achieveable using CRT which employ visible phosphors. If the curve in Figure 8 can truly be extrapolated as increasing as wavelength is decreased, the 320 nm phosphor CRT should allow even faster writing speeds.

At this point in the experiment, this particular CRT became gassy. A leak was found in the faceplate seal. Enough data had been taken on the 3M film to verify the writing speed mentioned, but inadequate data had been taken on other film types.

When testing did resume, it was found that the various film emulsions had begun to deteriorate. The films had been obtained prior to the arrival of the first CRT and were aging. While they were still usable, maximum O.D. obtainable and necessary exposure values had changed. This meant that comparison of measured writing speeds to calculated values for these films would have little or no meaning. Instead of obtaining fresh film, it was decided to simply compare the writing speed of the new CRT to that of a commercially available CRT, the Litton tube described previously, on any given film. Calculations made previously[1,4] indicate that the new 380 nm CRT should write on the mentioned films 7 to 10 times faster than existing CRT.

For purposes of comparison, both tubes were operated under exactly the same electrical and optical conditions.

Accelerating Voltage	- 20 kV
Beam Current	- 20 μA
Spot Size	- 0.006 inch
Sweep Length	- 1 inch
Sweep speed and exposure time	- variable

Fifteen to twenty measurements were made at any given exposure. Note that the 3M film had deteriorated to such an extent that 3 times the original exposures mentioned previously were necessary to achieve a given optical density. However, this would not affect the direct comparison of the two tubes. Table I lists the resultant optical densities for various exposures, listed in terms of effective writing speeds, on the different UV sensitive media for the new Westinghouse tube and for the Litton tube. The spectral sensitivities of Kalvar and Du Pont 201 are shown in Figures 10 and 11. At first glance, the writing speeds in the table appear extremely low, but that is not the case. The results can be placed in proper perspective by considering that employing electron optics capable of producing a 0.5 mil spot, 30 kV anode voltage and 40 μA beam current would result in an increase in energy density of about 500 times.

Another important consideration is the effect of reciprocity failure for the various films. If the amount of radiant energy delivered per scan per unit area is too low, the film will not respond to this energy regardless of the number of times the scan is repeated. The writing speeds over the 1 inch line scan never exceeded 20,000 inches per second for the most sensitive film and was usually about 3000 inches per second. The mode of operation was, for example, in keeping with that of previous tests made by the Du Pont De Nemours and Company on their Dylux films, and should be such that energy density present during a single sweep should be large enough to avoid the reciprocity failure effect.[7]

Table I. CRT Performance on Various Films

	Experimental Westinghouse CRT		Litton Type 4207	
Film Type	Effective Writing Speed (inches/sec)*	Optical Density	Effective Writing Speed (in/s)*	Optical Density
3M	10000 6670 5000 3330	0.5 0.8 1.2 1.5	500 333 250	0.6 [illegible] 1.5
Kalvar 163	3.33 2.50	0.28 0.32	0.5 0.25	0.12 0.29
Kalvar 203	10.0 5.0 3.3	0.15 0.24 0.35	1.0 0.5 0.33	0.10 0.20 0.37
Du Pont 201 (Cloudy Emulsion)	10.0 5.0 3.3 1.1	0.09 0.15 0.20 0.32	1.0 0.5	0.11 0.23
FC-135	1.0 0.5	0.06 0.11	0.17	0.06
FC-344	0.5	0.21	0.17	0.09

$$* \text{ Effective Writing Speed} = \frac{\text{Writing Speed of the beam}}{\text{Number of Refreshes}}$$

From the table, it can be seen that the new CRT writes on 3M dry silver film about 13 times faster than the commercially available tube operating under the same conditions. For Kalvar 163 and 203, the improvement is a factor of ten. Previous calculations indicated that this factor would only be 4.9, so here again it is seen that the CRT is performing better than expected. Note that the O.D. listed for Kalvar is a specular, transmission O.D. The standard method of quoting O.D. achieved on Kalvar is to cite the diffuse O.D. or the projection O.D. since it is a projection film not for direct viewing. Equipment for measurement of diffuse or projection O.D. was not available. A very small specular O.D. is all that would be required for most of the projection systems.

In their Data Sheet No. 48, Du Pont indicates that an effective writing rate of 1.3 inches/second was needed to achieve an O.D. of 0.7 on their 201 film using a Litton CRT with P-16 at 30 kV, 5 mil spot size, and 20 uA beam current. Considering the slightly larger spot size, lower high voltage, and degradation of the film characteristics, the data shown are consistent with the Du Pont data. At 20 kV and 0.006 inch spot size imaging rate shown by Du Pont should decrease to about 0.6 inch per second. Using the Litton Tube at a writing speed of 0.5 inch per second, as

shown in Table I, the film was exposed to an O.D. of about 0.2 instead of 0.7, but the emulsion had become cloudy and maximum O.D. achieveable on the film had degraded by a factor of 0.5. Thus, the results indicate good agreement with the Du Pont data. In the case of 201, a 7-fold increase in writing speed is achieved with the new tube.

Two samples of Photochromic films were made available for experimental purposes and an apparent increase in writing speed by a factor of 6 was obtained with the new CRT. PC-135 and PC-344 have half lives of 28 minutes and 72 minutes, respectively. Unfortunately, the densitometer used for O.D. measurement was located in a building that was a considerable distance away from the experimental setup. The delay between film exposure and O.D. measurement, plus the other factors already cited, account for the very low O.D. listed for these films. Here again, it is the improvement in writing speed shown which is the salient feature. In this case and in all others, theoretical expectations were met and exceeded.

Due to the performance of this tube, a great deal of interest both within and outside of government agencies developed. A long-lived P-16 type CRT replacement is a very useful device. For this reason, this tube has been loaned to ITEK Corporation who has proposed that it be used in government research programs involving a Pockels effect readout optical memory. Data from their investigations should be available shortly. Their theoretical analysis has indicated that this new CRT will perform better than any existing device in their systems.

A problem was encountered in the manufacturing of the 320 nm faceplates. Individual fibers and small fiber bundles were successfully fabricated. The first attempts to combine bundles of individual fibers were not successful; the resulting faceplate blanks contained pinholes. Various blanks were cycled through the fusing process from 3 to 6 times in order to make them vacuum tight. The problem evolved because this was an experimental glass with which the manufacturer had no previous experience. During this recycling, the extramural absorber (EMA) used may have diffused into the glass, or some degree of devitrification of the glass may have occurred, or any number of other unknown factors may have been introduced which reduced glass transmission. At any rate, the resultant CRT had very poor radiant output, and there was no point in carrying out an extensive analysis. The problem should not occur again since the manufacturer now knows the temperature at which the blanks do fuse.

CONCLUSIONS

The experimental analysis of two new UV emitting fiber optic faceplate CRT has been completed. One of the two tubes can be considered to be a much improved version of existing tubes which use P-16 for their phosphor. The new CRT has been shown theoretically and experimentally to have nearly an order of magnitude increase in UV emission centered around 380 nm, when compared to presently available tubes operated under the same conditions. The new CRT is capable of writing on various UV sensitive recording media 7 to 13 times faster than existing CRT, depending upon the spectral match of radiant output of the tube to film sensitivity.

The results on the 320 nm tube were ill-defined due to the problem incurred during faceplate fabrication. These are not basic problems, however, and

would not affect future tube fabrication. Both the phosphor and the faceplate glass developments for this CRT were highly successful.

ACKNOWLEDGMENTS

We would like to thank Dr. Elliott Schlam for his comments on this work. Also, we are grateful to Litton Industries for use of their CRT and, in particular, to Dr. G. Pokorny, Dr. J. Wurtz, and Mr. F. Oakes of Litton. We are also grateful to Dr. R. Bowman of National Cash Register, Dr. R. Dessauer and Mr. E. Abramson of Du Pont, and Mr. K. Kramer and Dr. P. Gleichauf of Stromberg Datagraphix for their film samples and comments concerning film characteristics.

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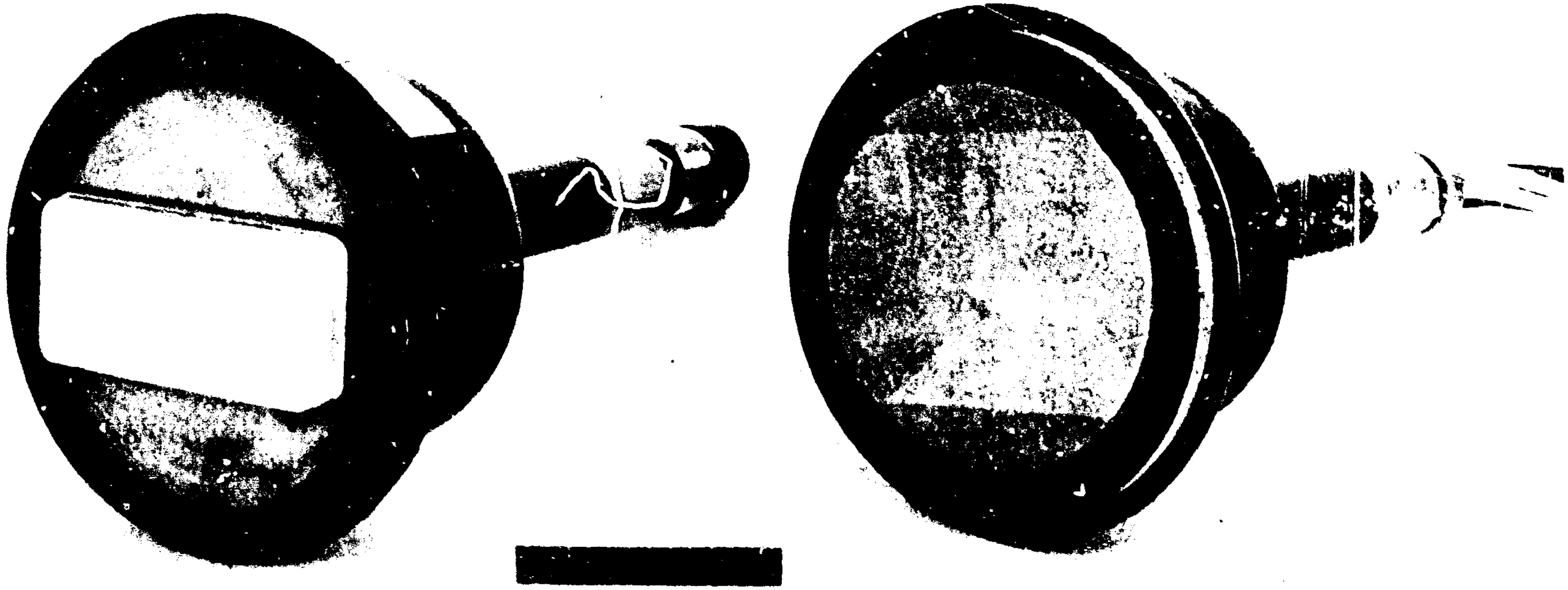

Figure 1. 380 nm and 320 nm Cathode Ray Tubes

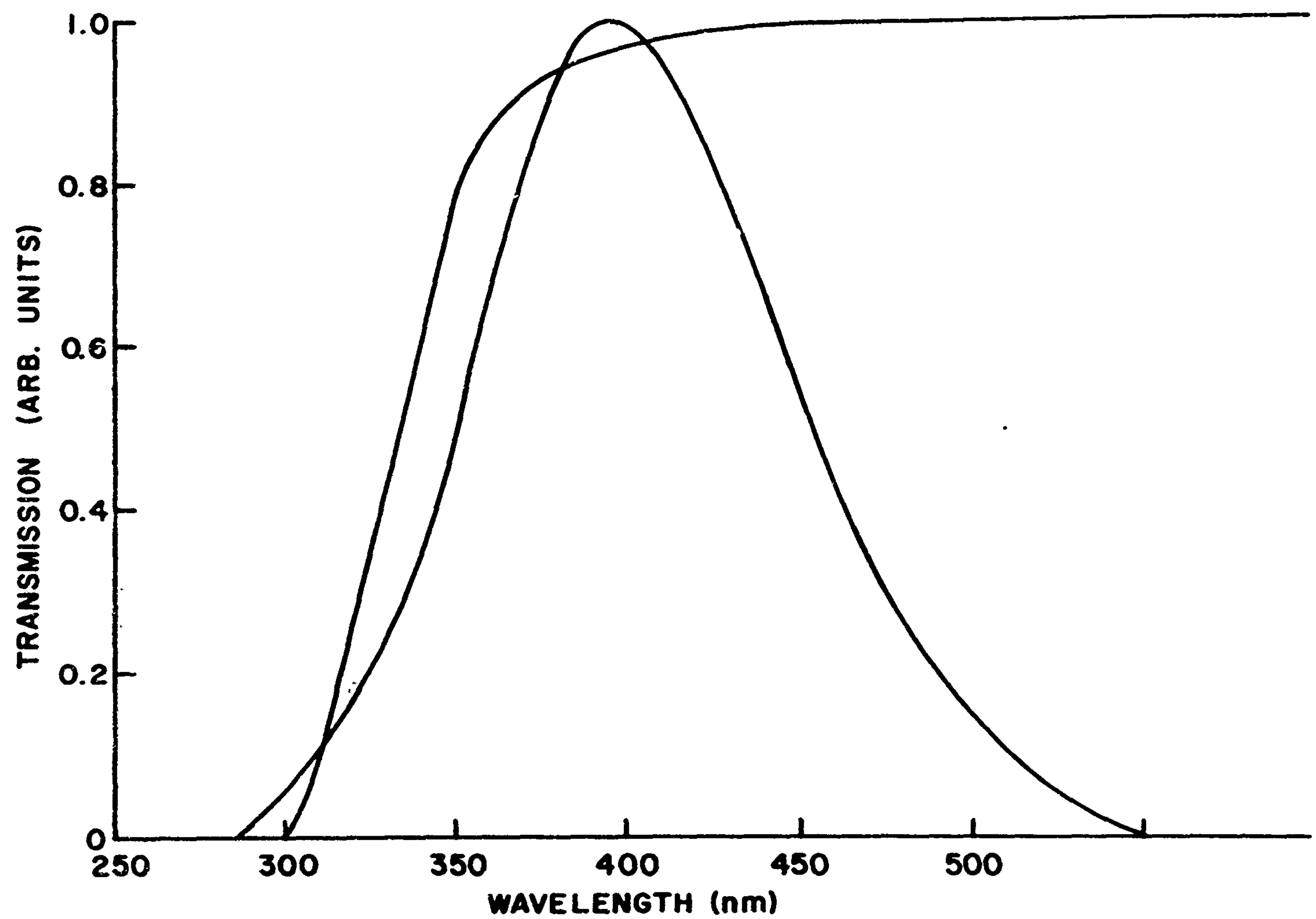

Figure 2. Normalized Output Spectrum of $ZnSiO_4:TiO_2$ and Spectral Transmission of the New 380 nm Faceplate

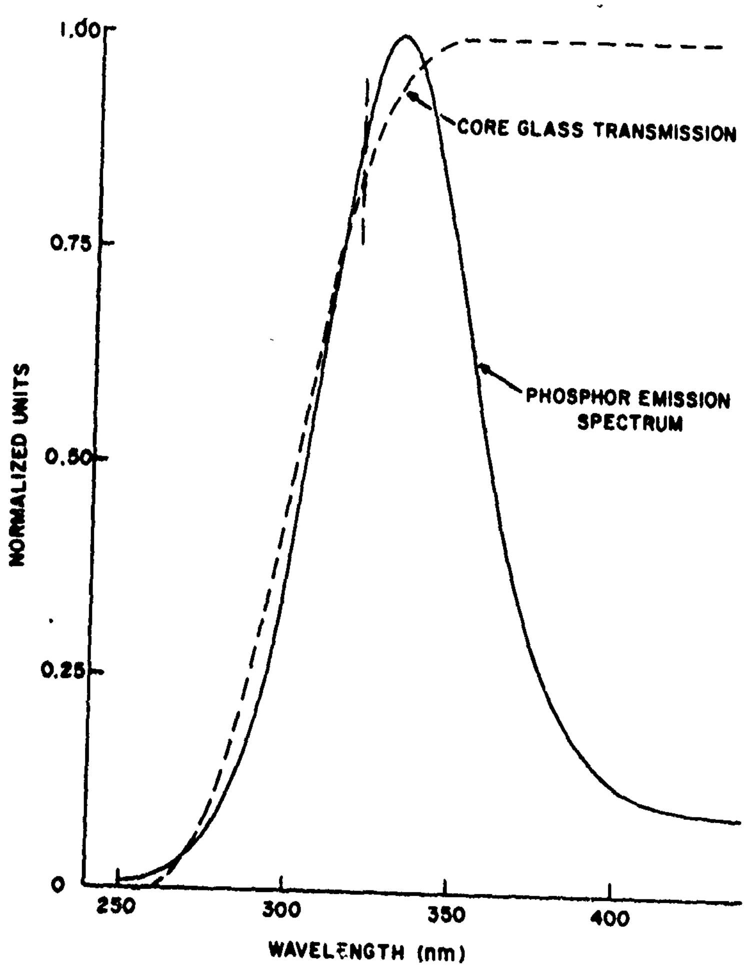

Figure 3. Normalized Output Spectrum of $Sr_2ZnSi_2O_7$:Pb and Spectral Transmission of the New 320 nm Faceplate

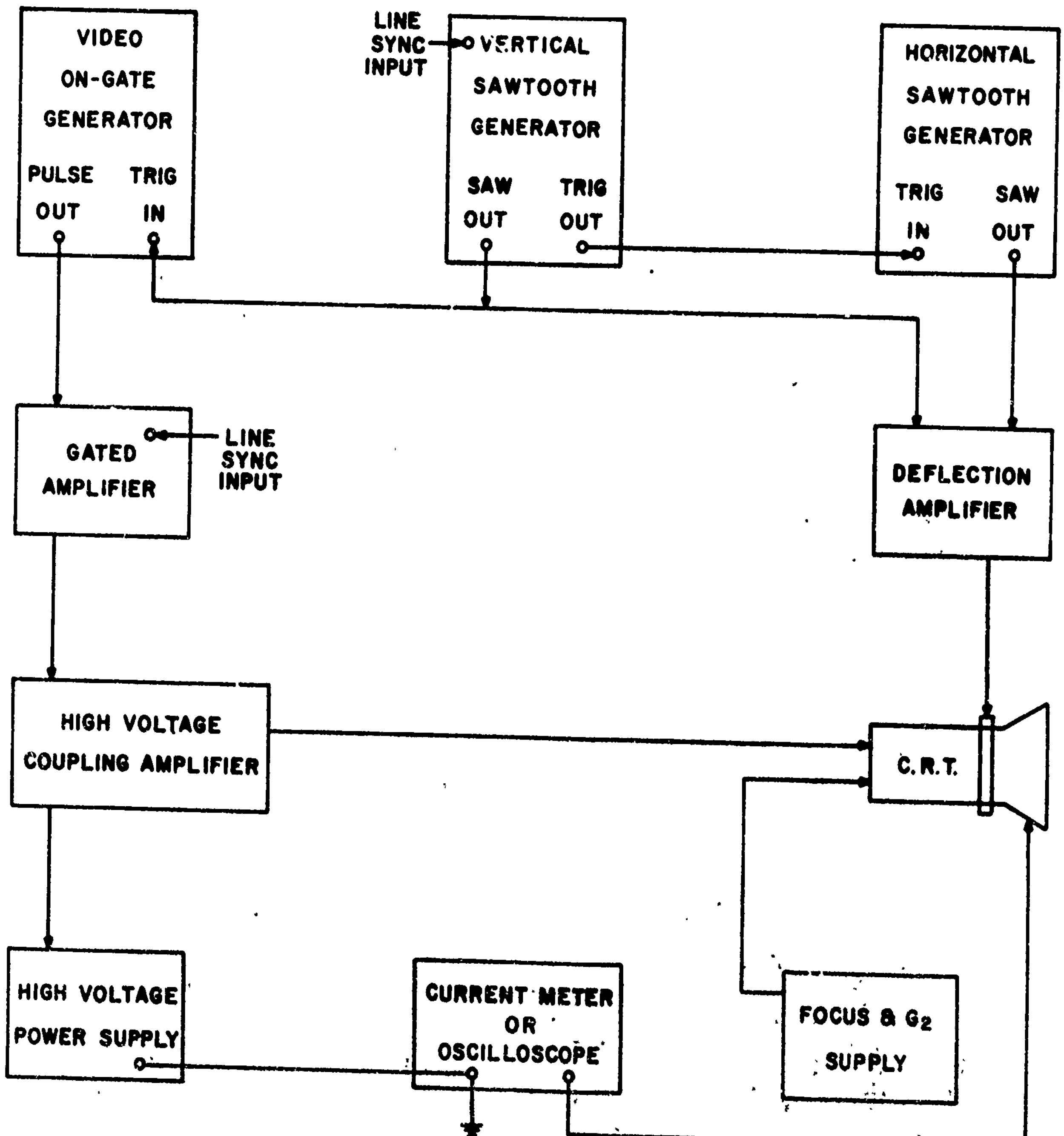

Figure 4. Block Diagram of Electronics

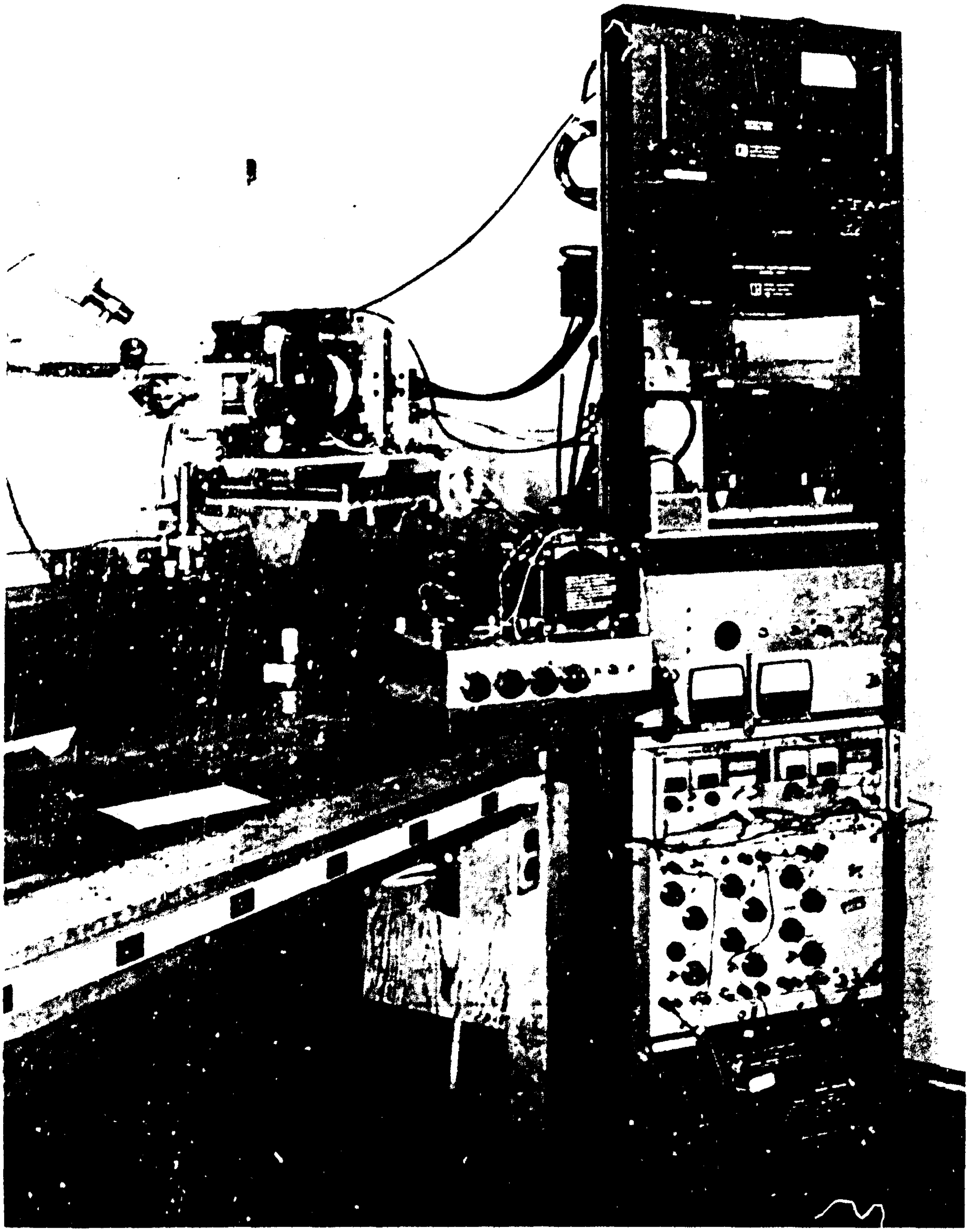

Figure 5. Experimental Test Rack

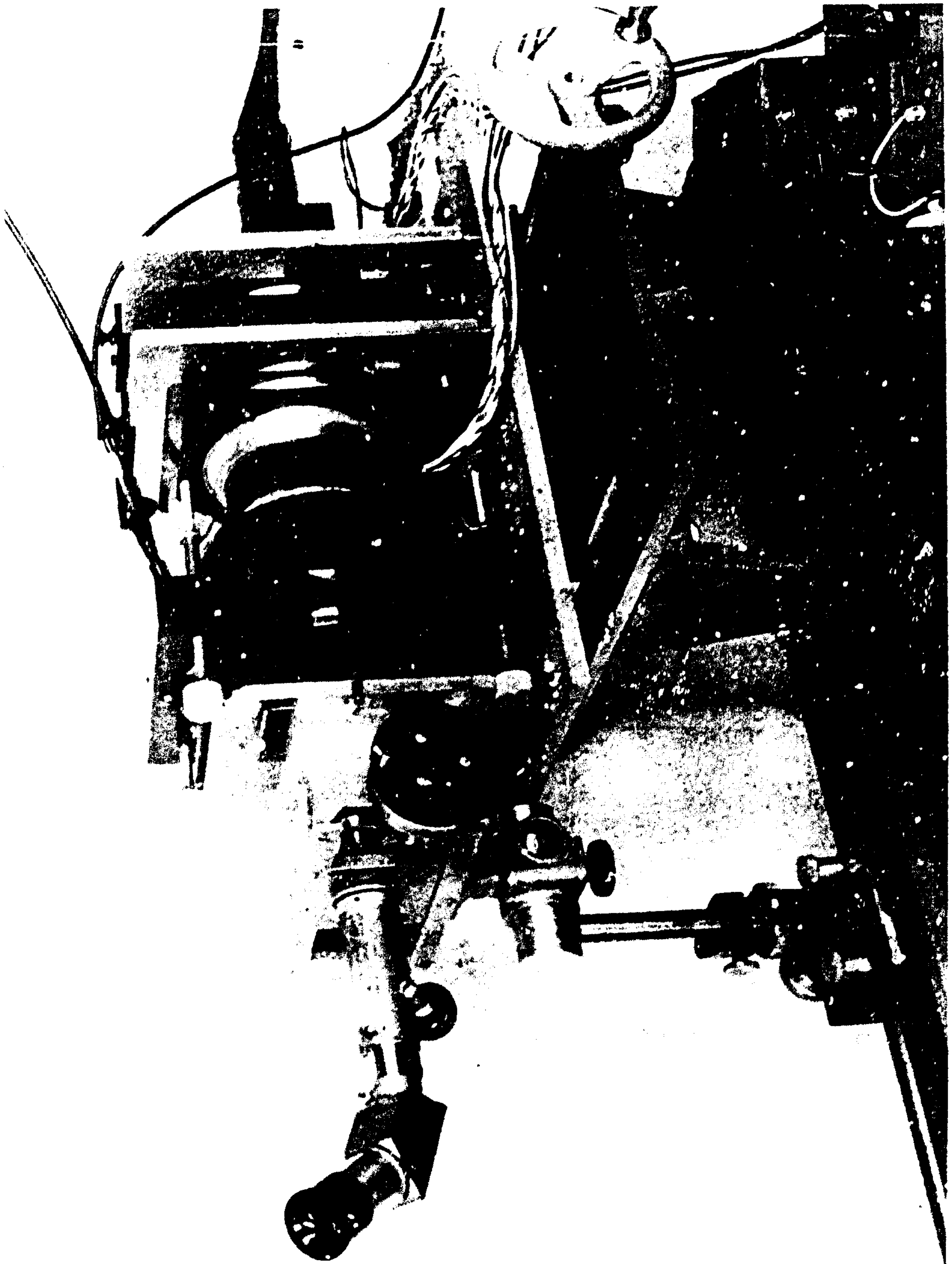

Figure 6. CRT Mounting Assembly

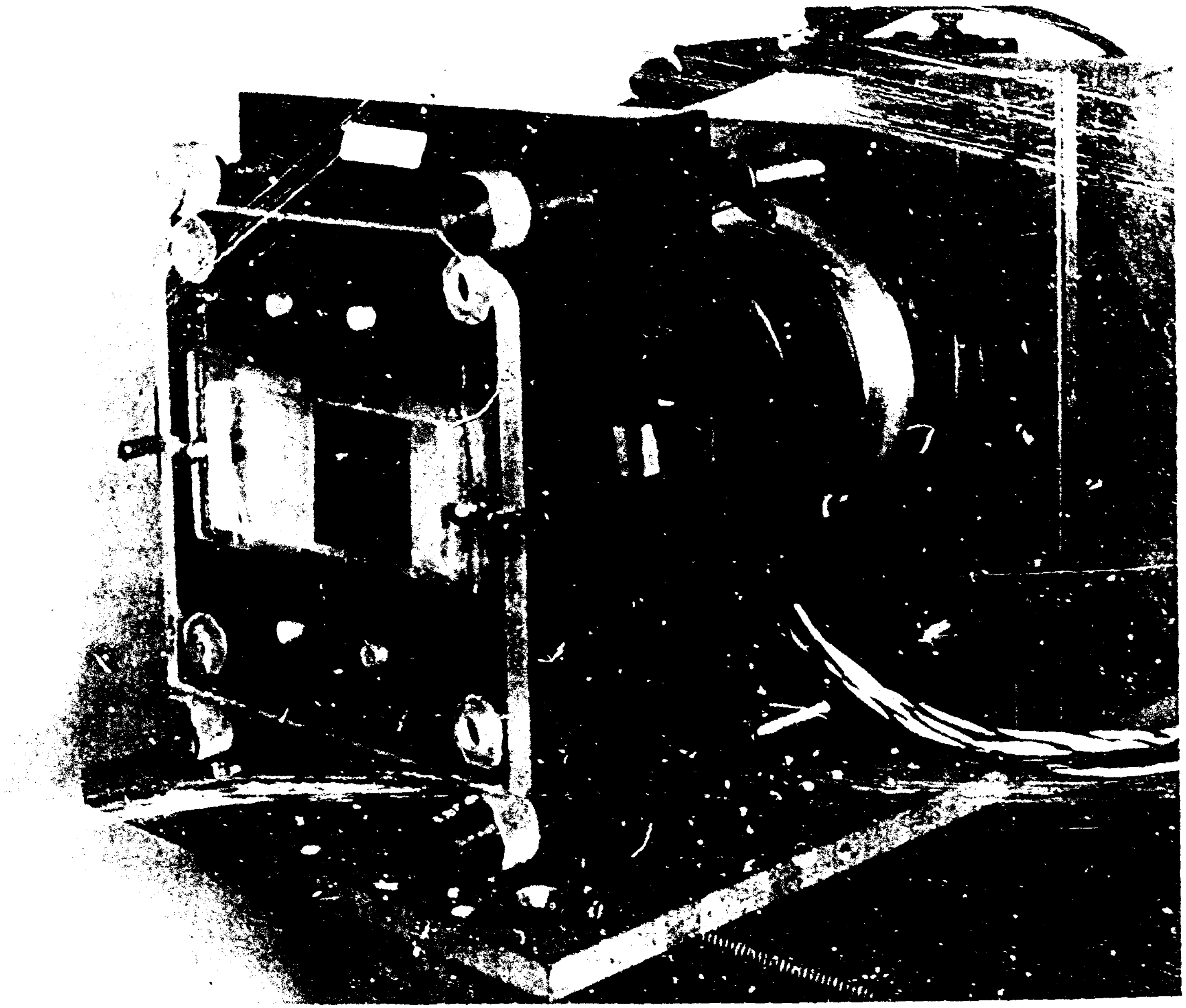

Figure 7. Pressure Plate

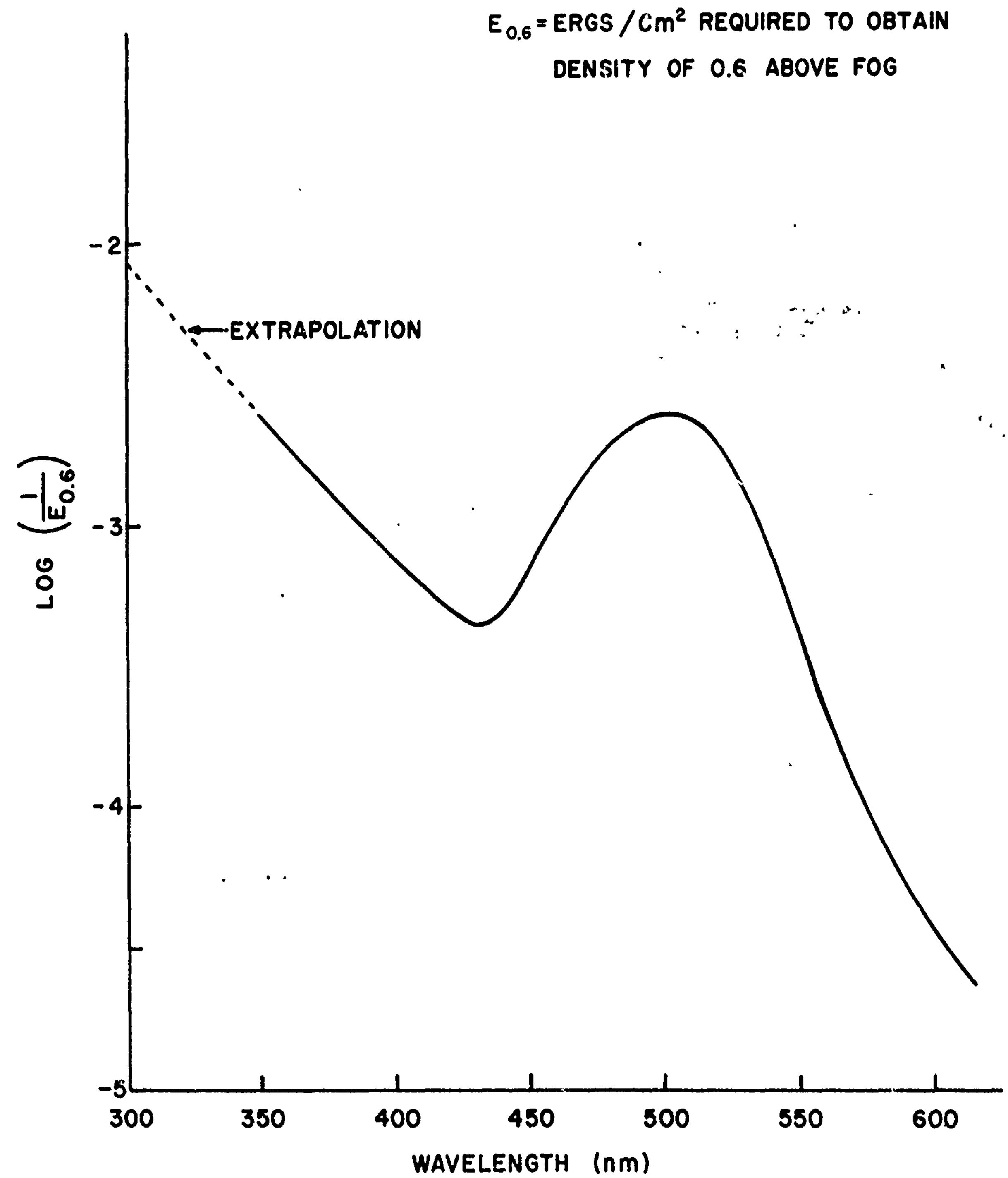

Figure 8. Spectral Sensitivity of 3M Type 784

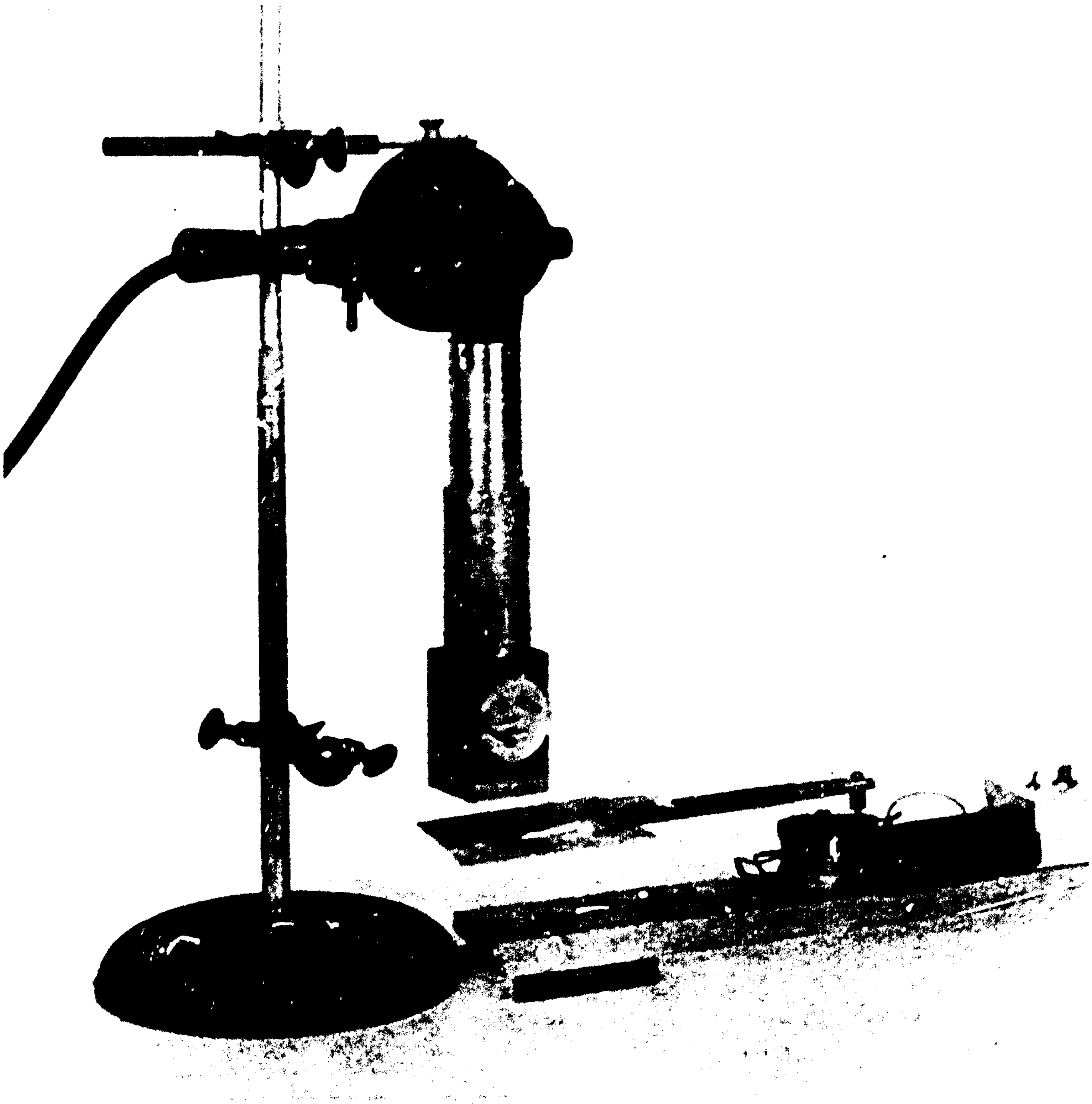

Figure 9. Heat Processing Unit

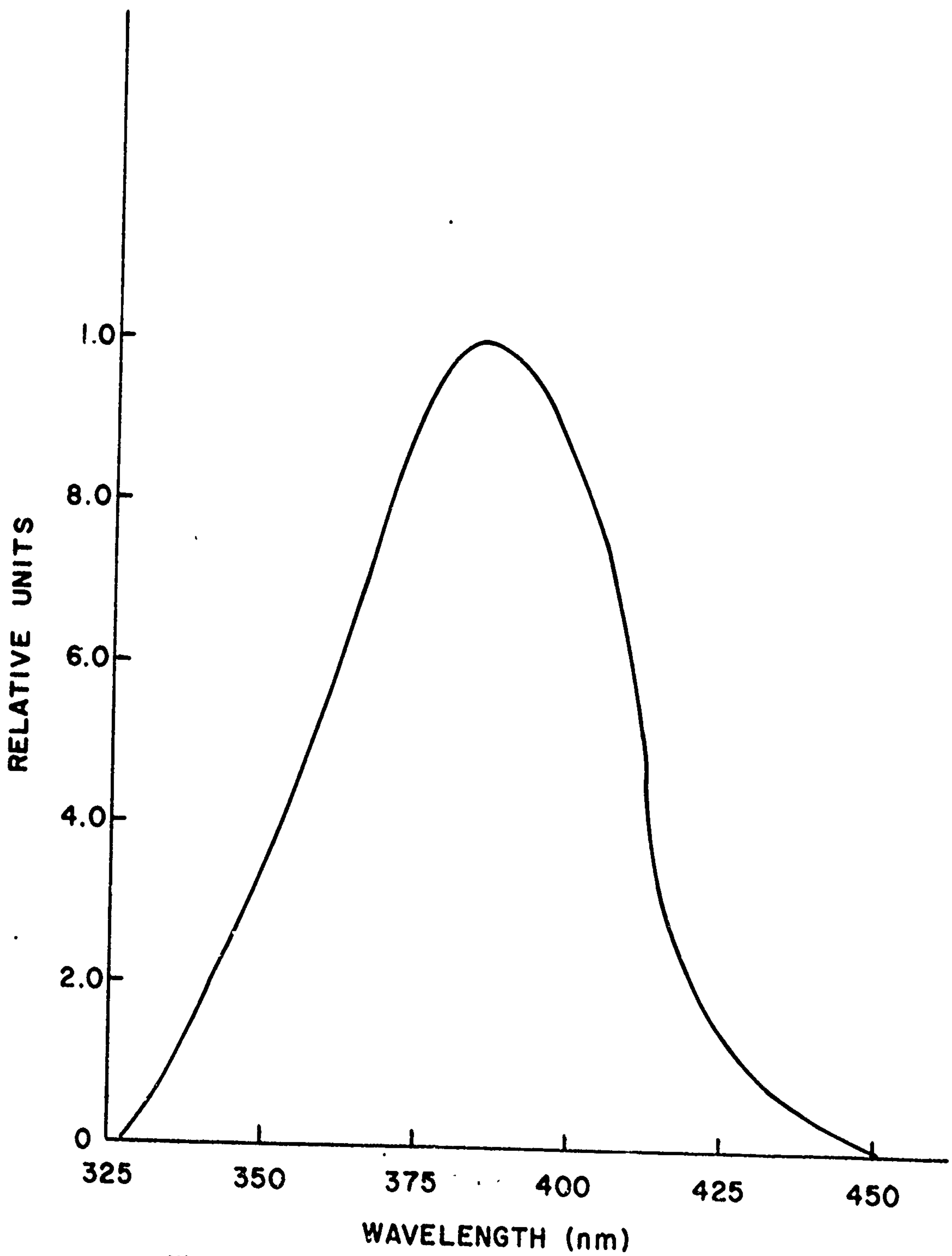

Figure 10. Spectral Sensitivity of Kalvar

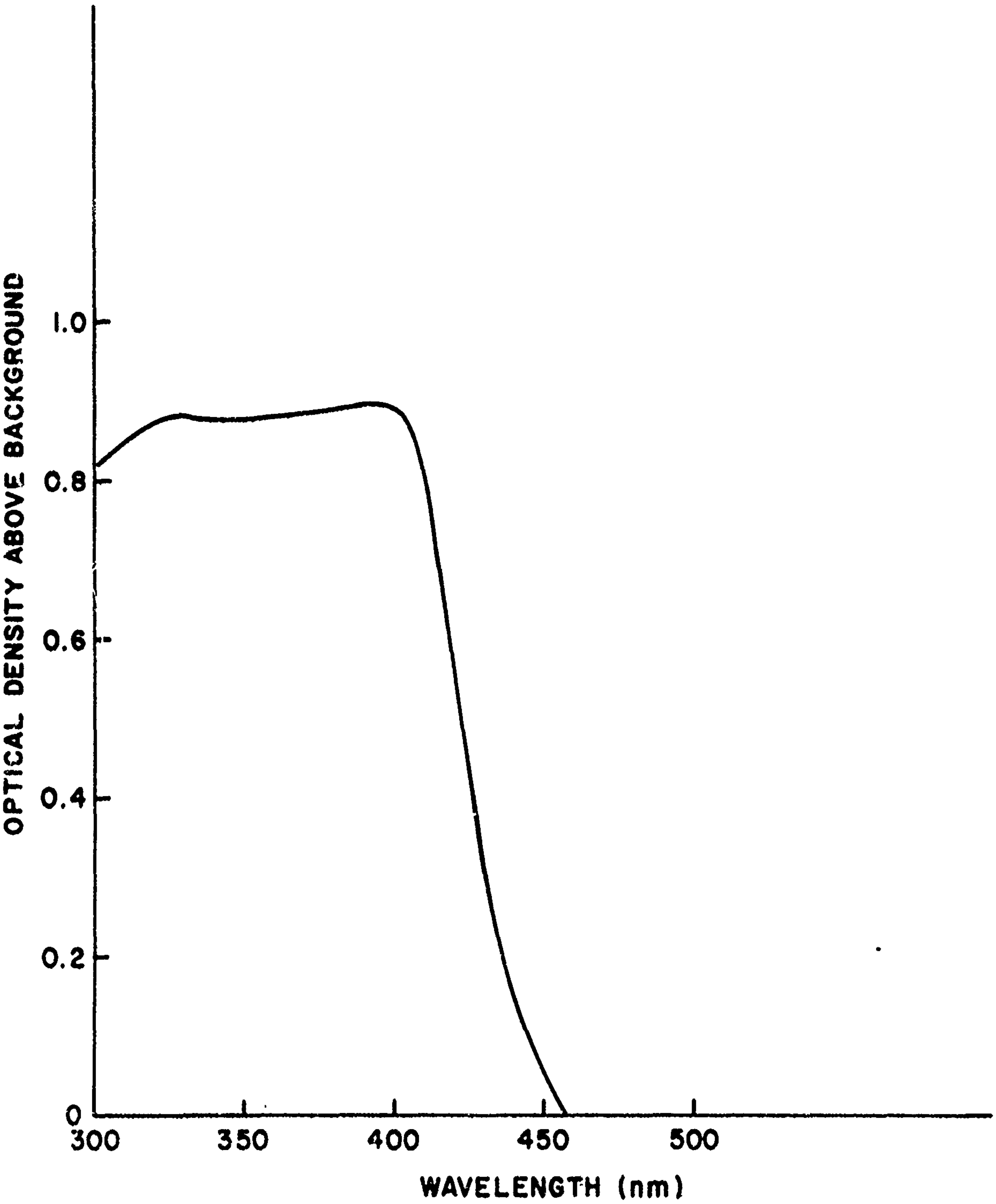

Figure 11. Spectral Sensitivity of Du Pont 201